

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)**ScienceDirect**

Procedia Engineering 75 (2014) 45 – 50

**Procedia  
Engineering**[www.elsevier.com/locate/procedia](http://www.elsevier.com/locate/procedia)**MRS Singapore - ICMAT Symposia Proceedings**

International Conference on Materials for Advanced Technologies: Symposium W

**Non-contact measurement techniques for structural health  
monitoring****W.H. Ong, W.K. Chiu\****Department of Mechanical & Aerospace Engineering, Monash University, Wellington Road, Clayton, 3168, Australia***Abstract**

The application of 3D scanning laser vibrometry for visualising stress wave propagation in a specimen with a non-surface penetrating defect is presented. The results support the need for a good understanding of the 3D velocity fluctuation measurements to provide a good insight of the propagation of the stress wave over a given region. It will be shown that a full knowledge of the velocity field will facilitate an understanding on the interaction of the various wave modes with the defect in the structure. For the purpose of this paper, a flat aluminium test plate with non-surface penetrating defect will be used to illustrate the application of this form of non-contact measurement technique for this stress wave visualisation work. It will be shown that the modal content and the time-development of the incident and the scattered wave modes can be evaluated with this type of measurement technique.

© 2013 The Authors. Published by Elsevier Ltd.

Selection and/or peer-review under responsibility of the scientific committee of Symposium [Advanced Structural and Functional Materials for Protection] – ICMAT.

*Keywords:* Lamb wave, PZT, 3D laser vibrometry, damage, partial depth hole, visualisation, structural health monitoring.**Nomenclature**

$V$	velocity (mm/s)
$h$	thickness (mm)
$t$	time (sec)

\* Corresponding author. Tel.: +61 3 9905 5595; fax: +613 9905 1825.

*E-mail address:* [wing.kong.chiu@monash.edu](mailto:wing.kong.chiu@monash.edu)

*Greek symbols* $\lambda$  wavelength (mm)*Subscripts**scatter* scatter component*baseline* undamaged (baseline) component*damage* damaged component*L* longitudinal component*R* radial component*T* Tangential component**1. Introduction**

Lamb wave technology has been demonstrated to be successful in detection of damage by a number of authors (Staszewski et al [1], Alleyne & Cawley [2]). The work done by Ryles et al [3] is representative of the capabilities of Lamb waves. By measuring and quantifying the differences between a baseline flawless specimen and a fatigued specimen, cracks could be detected as well as quantified. While there are a large number of successful works performed in this field, they are often performed on highly idealised specimens. As the state of the field matures the novelty in using idealised specimens such as flat plates is wearing out. Consequently, in recent times it has been necessary to explore more complex geometries. Ong et al, [4] adopted a similar technique for damage quantification and attempted Lamb wave based damage quantification on a specimen representative of a lower wing skin. The lower wing skin structure deviates from a flat plate through the introduction of stiffeners of larger thickness. It was shown that such real world geometry significantly alters the behaviour of Lamb wave based damage detection. This works demonstrate the need for a good understanding of the entire scattered field to ensure that the defect to be monitored at sensor locations where the optimal degree of response can be measured. The work reported by Ong et al [4] demonstrated the effects of geometry changes on the propagation of stress wave in a realistic aircraft structure. The use of a uni-directional scanning laser vibrometry greatly assisted in visualising this effect. More importantly, this non-contact means of measurement also allowed for the investigation of the changes in the scattered field due to the presence of a structural defect located within this changing region of geometry changes.

Recently, Doherty and Chiu [5] reported on the potential use of propagating stress waves for in-situ monitoring of fatigue crack development from hard-to-inspect weep holes in the wing spars of aging aircraft with permanently bonded, low-profile piezoelectric disc actuators. They provided new experimental evidence showing an interesting scattering phenomenon at the defect and demonstrated that this phenomenon could be used to monitor the development of a fatigue crack growing on the blind side of an open hole. The propagating stress waves excited in the riser by the actuators were visualised using 3D laser vibrometry. To support their experimental findings, a series of finite element analyses of the problem were conducted (Doherty & Chiu [6]). Good agreement with the experimental results was obtained.

Their analysis suggested that when an incident wave field impinges on an open hole, a boundary condition is established on the free surface of the hole. This condition gives rise to a wave that propagates along the free surface that will interact with the defect that is otherwise hidden from direct line-of-sight of the incident wave. The interaction between the wave propagating along the free-surface of the hole and the defect resulted in a scattered wave field. The intensity of this scattered wave field can thus be measured to determine the size of the defect present. Whilst a uni-directional scanning laser vibrometry was adequate for the works described by Ong

& Chiu [4], the works reported by Doherty & Chiu [5] could only be achieved with a series of 3D scanning laser vibrometry. The 3D laser vibrometry allowed for the in-plane and out-of-plane velocity fluctuations to be measured and scanned over a given region on the structure. With the full definition of the propagation of the stress wave in this region, a better understanding of the interaction between the incident wave modes and the defect can be achieved. This greatly assisted with the identification of the appropriate sensor location to better detect and monitor the development of the defect within the structure.

The significance of 3D scanning laser vibrometry in visualising the propagation of stress wave in a plate-like structure and in visualising the scattered field due to the presence of a non-surface penetrating defect will be shown in this paper. To illustrate this, a series of 3D scanning laser vibrometry experiments on 2 aluminium test specimens with varying partial depth damage will be presented. The visual stress wave field due to scattering of the incident stress wave by this non-surface penetrating defect will be shown. These results will show how that the use of a 3D scanning laser vibrometry can greatly enhance the understanding of the problem at hand. More importantly, the full definition of the scattered field can also assist with the appropriate placement of sensors to detect and monitor the development of this type of defects.

## 2. Description of test specimen

The test specimens used in this investigation is made from 6 mm thick aluminium. A partial depth hole is machined on one side of the test plate as shown in Fig 1. A 20 mm diameter partial depth hole was used to simulate a non-surface penetrating defect. The depth of the defect was firstly set at 0.25h (1.5 mm) and was increased to 0.5h (3 mm) and 0.75h (4.5 mm), where h=6 mm (see Fig 1).

Two 10 mm piezoceramic (PZT) actuators (Actuators A and B) were bonded to the edge of the specimen as shown in Fig 1. For the purpose of this paper, only the results from Actuator A are presented. These PZT actuators were excited independently of each other and in a given set of experiment only one of them was used. A 5 cycle Hanning windowed sinusoidal tone burst with a centre frequency of 300 kHz was used to excite these PZT actuators thereby initiating a stress wave that propagated in the test specimen.

Fig 1 also indicates the side of the flat plate that was scanned during the experiment. The coordinate system used to define the direction of measurement is also shown in Figure 1. The in-plane components are defined by the x- and y-direction components, whilst the z-direction defines the out-of-plane component. Prior to the introduction of the non-surface penetrating defect, the undamaged specimen was scanned to obtain a baseline. It was then removed from the test rig to introduce the desire partial depth damage and re-position on the test rig for re-scanning. The damage was progressive increased following each scan. The scattering of the velocity field from the inclusion of damage can then be visualised by calculating the subtraction of the damaged velocity field from the defect free baseline velocity field for each time step:

$$V_{scatter}(t) = |V_{baseline}(t) - V_{damage}(t)| \quad (1)$$

A computer controlled laser vibrometry rig pictured in Figure 2 was developed at Monash University for use in this investigation (see also [1]). A Parker Automation 404XE Electromechanical Positioning System with LV233 stepper motors was used to position the specimen. The stepper motors, capable of a resolution of 5000 steps per millimetre, enabled accurate and consistent positioning of the mounted specimen. Custom software was developed in MATLAB to synchronise positioning with signal generation and data acquisition.

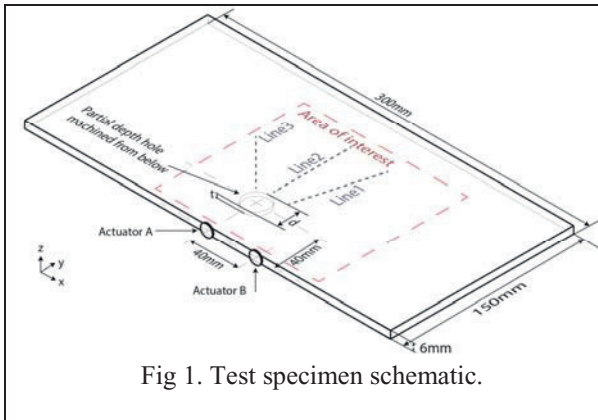


Fig 1. Test specimen schematic.



Fig 2. Experimental test setup.

Lamb wave responses of the plate were sensed using a three axis laser vibrometer. A Polytec CLV 3D sensor head with left, right and top beams, was positioned and focused to measure three components of velocity ( $V_L$ ,  $V_R$  and  $V_T$ ) of the specimen at any given position. The 1.5 MHz modified CLV-M030.B decoder module output a voltage directly proportional to the surface velocity with a factor of 5 mm/s/V. The velocity signals were later converted to their orthogonal components using the supplied equations (Polytec [7]), where the angle between the optical axis and the top laser beam is  $12^\circ$  with a 160 mm focal length lens. The test setup is shown in Fig 2. Data acquisition was performed with a National Instruments PCI-6115 board and BNC-2110 block at 10 MHz and stored in the controlling computer. Input capture from the laser was hardware triggered by the rising edge of the excitation signal. This was essential for ensemble averaging and synchronisation of spatially varying data. In this case, 16 time series averages were performed at each scan location to enhance the signal-to-noise ratio for a series length of 1 millisecond. The excitation signals were amplified from the 1 Vp-p 4MHz output to 73 Vp-p with a Krohn-Hite Model 7602 Wideband Power Amplifier.

Using this test facility, the entire wave field in the region of interest can be scanned. The resulting time-series measured at each measurement point in the scanning region can be collated and processes using a MatLab script to generate a time-varying visualisation representation of the stress field. The propagation of the stress field in 3-direction can be visualised. Using equation (1), the scattered field due to the presence of the defect can also be visualised. Given that the temporal and spatial information of the stress wave in the scanned region is acquired, the dispersion characteristics of the stress wave present can be calculated by performing a 2D FFT on the data acquired. This will assist with ensuring that the signals acquired are consistent the expected physical properties of the expected stress wave modes that can exist on the test plate.

### 3. Experimental results and discussions

The test plate without this damage was firstly scanned to obtain the baseline. To understand the modal content of the velocity fields, the spatial and temporal data were transformed to wavenumber and frequency as shown in Figures 3(a) – 3(c) taken along Line 1 (see Fig 1). Against each of these plots, the analytical Ao, So and the SHo modes are included for comparison. It is evident from these plots that the excited stress wave comprises mainly the So and the SHo modes. Note that the SHo mode could only be measured with the in-plane velocity measurement.

To assist with the visualisation of the scattering effects of partial depth hole, the acquired velocity data were processed using equation (1). For brevity, only the results obtained with 4.5 mm partial depth hole is presented. The results are plotted in Fig 4-6. These results are presented in a manner to show the time-progression of the

scattered wave field in the x-, y- and z-directions. The wavelength of the scattered wave shown in Fig 4 is approximately 13 mm. This is consistent with the SHo wave mode. It is interesting to note that the scattered wave field is more prominent outside of the partial depth damage and appears to be guided by the circumference of the partial depth defect, even though these measurements were taken on the flat side of the test specimen. The scattering shown in Fig 5 comprises of 2 components. One can be attributed to the specular reflection of the incident wave and one that is transmitted through the defect. The wavelengths of these scattered waves are shown in Fig 5. They are 20 mm and 13 mm for the reflected and the transmitted wave field, respectively. From these wavelengths information, it is deduced that the specularly reflected wave comprises mainly of the SHo whilst the transmitted wave mode is dominantly So. The results in Fig 6 show out-of-plane component of the scattered field. The wavelength of the transmitted wave is approximately 12 mm. It is also interesting to note the existence of the interaction of the wave modes that are internally reflected within the partial depth hole. Although this feature is a pleasing visual feature, the inability to full characterise this wave mode render its use limited from the perspective of structural health monitoring.

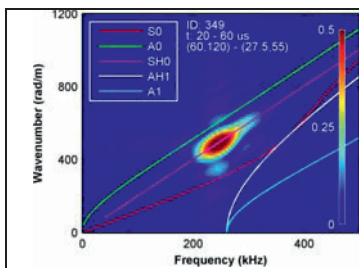


Fig 3(a): x-direction velocity

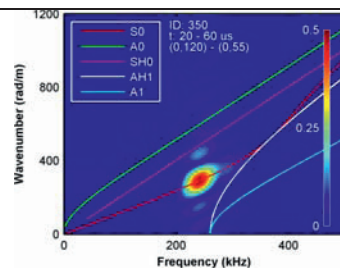


Fig 3(b): y-direction velocity

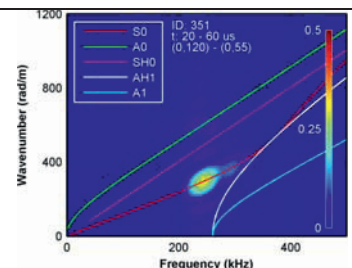


Fig 3(c): z-direction velocity

#### 4. Conclusions

The application of 3D scanning laser vibrometry for visualising stress wave propagation in a specimen with a non-surface penetrating defect is presented. The results support the need for a good understanding of the 3D velocity fluctuation measurements to provide a good insight of the propagation of the stress wave over a given region. A full knowledge of the velocity field will facilitate an understanding on the interaction of the various wave modes with the defect in the structure. This non-contact measurement tool can be used to define the modal content of the incident stress wave. It can also be used to provide a means of visualising the time development of the scattered field. This can potentially be used to assist with the appropriate placement of the actuator. Equally as important, it also provided a good insight into the how the various modal components of the incident stress wave energy are scattered by the defect present. The definition of the scattered field using this non-contact measurement technique can be used to visualisation the energy flow and therefore providing a means for appropriate sensor location.

#### Acknowledgements

The financial support provided by the US Navy Office of Naval Research (N62909-12-1-7005) is gratefully acknowledged.

#### References

- [1] Staszewski, W.J., B.C. Lee, and R. Traynor, (2007) *Fatigue crack detection in metallic structures with Lamb waves and 3D laser vibrometry*. Measurement Science & Technology, 2007. 18(3): p. 727-739.



- [2] Alleyne, D.N. and P. Cawley, (1992) *The Interaction of Lamb Waves with Defects*. Ieee Transactions on Ultrasonics Ferroelectrics and Frequency Control, 1992. 39(3): p. 381-397.
- [3] Ryles, M., et al., *Comparative study of nonlinear acoustic and Lamb wave techniques for fatigue crack detection in metallic structures*. Fatigue & Fracture of Engineering Materials & Structures, 2008. 31(8): p. 674-683.
- [4] Ong, W.H. and W.K. Chiu, (2010) *Damage Quantification in Plates Using Lamb Waves*, in *Australasian Congress on Applied Mechanics*. 2010: Perth, Australia.
- [5] Doherty, C. and W.K. Chiu, *Scattering of ultrasonic-guided waves for health monitoring of fuel weep holes*. Structural Health Monitoring, 2011.
- [6] Doherty, C. and W.K. Chiu, *Three-dimensional finite element modelling of ultrasonic-guided wave scattering from fuel weep holes*. Structural Health Monitoring, 2012.
- [7] Polytec. (2005). User Manual: 3D Laser Vibrometer

